REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
06-28-2005

REPRINT

4. TITLE AND SUBTITLE
Sunspot Cycle 24: Smallest Cycle in 100 Years?

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
L. Svalgaard*, E.W. Cliver, and Y. Kamide*

5d. PROJECT NUMBER
1010

5e. TASK NUMBER
RD

5f. WORK UNIT NUMBER
A1

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory/VSBXS
29 Randolph Road
Hanscom AFB MA 01731-3010

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/VSBXS

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-VS-HA-TR-2005-1075

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited.

*Solar-Terrestrial Environment Lab, Nagoya University, Toyokawa, JAPAN

13. SUPPLEMENTARY NOTES
REPRINTED FROM: GEOPHYSICAL RESEARCH LETTERS, Vol 32, L01104, doi: 10.1029/2004GL021664, 2005.

14. ABSTRACT
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15. SUBJECT TERMS
Sunspot cycle
Solar polar magnetic fields
Cycle 2+ prediction

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON: E.W. Cliver
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area code)
UNCLAS	UNCLAS	UNCLAS	SAR		781-377-3975

Standard Form 298 (Rev. 8-98)

20050705 033

AFRL-VS-HA-TR-2005-1075

GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L01104, doi:10.1029/2004GL021664, 2005

Sunspot cycle 24: Smallest cycle in 100 years?

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Received 3 October 2004; revised 10 November 2004; accepted 9 December 2004; published 11 January 2005.

[1] Predicting the peak amplitude of the sunspot cycle is a key goal of solar-terrestrial physics. The precursor method currently favored for such predictions is based on the dynamo model in which large-scale polar fields on the decline of the 11-year solar cycle are converted to toroidal (sunspot) fields during the subsequent cycle. The strength of the polar fields during the decay of one cycle is assumed to be an indicator of peak sunspot activity for the following cycle. Polar fields reach their peak amplitude several years after sunspot maximum; the time of peak strength is signaled by the onset of a strong annual modulation of polar fields due to the $7\frac{1}{4}°$ tilt of the solar equator to the ecliptic plane. Using direct polar field measurements, now available for four solar cycles, we predict that the approaching solar cycle 24 (~2011 maximum) will have a peak smoothed monthly sunspot number of 75 ± 8, making it potentially the smallest cycle in the last 100 years. **Citation:** Svalgaard, L., E. W. Cliver, and Y. Kamide (2005), Sunspot cycle 24: Smallest cycle in 100 years?, *Geophys. Res. Lett.*, *32*, L01104, doi:10.1029/2004GL021664.

1. Introduction

[2] The solar cycle is currently thought to be driven by a self-exciting oscillating dynamo that converts poloidal magnetic fields into the azimuthal fields erupting as solar active regions and sunspots [*Dikpati et al.*, 2004]. At present, our limited understanding of the solar cycle does not allow predictions of future solar activity from theory. Prediction of solar activity is important for planning and management of space missions, communications, and power systems [*National Oceanic and Atmospheric Administration*, 2004; *Wilson et al.*, 1999]. Most solar cycles seem to be reasonably well characterized by a single parameter: Rmax, the maximum smoothed monthly sunspot number [*Waldmeier*, 1955; *Hathaway et al.*, 1994, 2002]. Predicting the amplitude, shape, and duration of the next cycle thus concentrates on predicting Rmax for the cycle.

[3] Empirical predictions fall in two broad categories, statistical methods and precursor methods. Statistical methods assume that the long time-series of sunspot numbers (reliably determined from 1850 to the present) carries information about the underlying physics that can be extracted and exploited for forecasting by statistical analysis [*Sello*, 2001]. Precursor methods assume that some properties of the current cycle have predictive power for the next cycle. *Schatten et al.* [1978] pioneered the use of the solar polar magnetic field as a precursor indicator. Because the poloidal field is an important ingredient in seeding the dynamo mechanism, the polar field precursor method appears to be rooted in solid physics. The success rate of predictions made very early before cycle onset has been mixed, however (cycle 21: observed 165 vs. predicted 140 ± 20 [*Schatten et al.*, 1978]; cycle 22: 159 vs. 109 ± 20 [*Schatten and Hedin*, 1984]; cycle 23: 121 vs. 170 ± 20 [*Schatten and Pesnell*, 1993]). Several reasons exist for this: the solar polar fields are difficult to measure and proxies (e.g., geomagnetic activity indices) were often used in their place, the historical database is short, and it was not clear when within the cycle the polar fields would be best utilized. As we approach minimum and the new cycle gets underway, the solar polar field precursor method improves markedly (cycle 22: 159 vs. 170 ± 30 [*Schatten and Sofia*, 1987]; cycle 23: 121 vs. 138 ± 30 [*Schatten et al.*, 1996]). The improvements also result from the use of actually measured polar fields rather than proxies. It is a strength of the polar field precursor method that the predictions improve in this manner. This paper suggests a novel way of applying the polar field precursor well before sunspot minimum.

2. Data and Methodology

[4] The sun's magnetic field near the poles has been measured regularly with the required sensitivity at Mount Wilson (MWO [*Ulrich et al.*, 2002], since 1967) and Wilcox Solar Observatories (WSO [*Svalgaard et al.*, 1978], since 1976). The pioneering observations by the Babcocks [*Babcock and Babcock*, 1955; *Babcock*, 1959] showed that the polar fields were very strong in 1952–54, then reversing sign during 1957–1958. Scattered measurements during the 1960s [*Severny*, 1971] confirmed that the polar fields reach maximum values at or near sunspot minimum and reverse sign at or near sunspot maximum. The MWO and WSO measurements extending to the present show the same general behavior.

[5] Instrumental details have been essentially unchanged at WSO since its inception: the solar image is scanned with a 175″ by 175″ square aperture (1/11th of the solar diameter). The image is divided into 11 scan lines parallel to the solar equator. The instrument measures the line-of-sight component of the magnetic field using the 5250 Å Fe I line. A typical error for both the magnetic signal and the zero-level is 5 μTesla. This very low noise level combined with the fact that no changes to the instrument and the data reduction have taken place are major reasons for basing the present paper on the WSO data. For the purpose of this Letter, we operationally define the solar polar fields as the net magnetic line-of-sight component measured through the polemost apertures at WSO along the central meridian on

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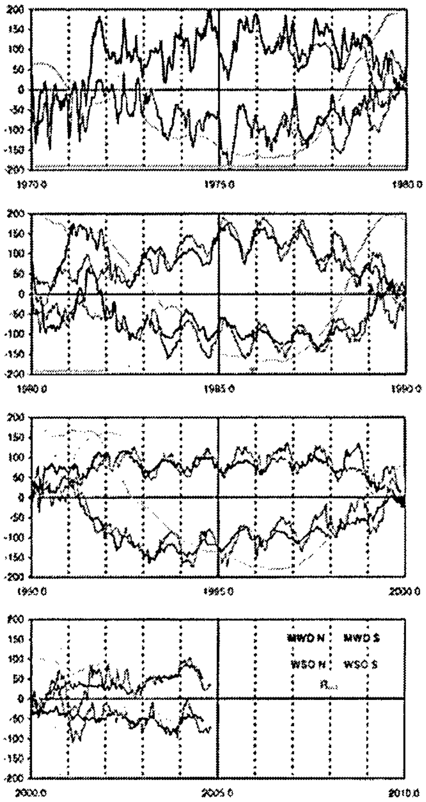

Figure 1. Observed polar fields for each decade since 1970. MWO N-polar fields (dark blue), S-polar fields (light blue). WSO N-polar fields (dark red), S-polar fields (light red). The average WSO N-polar fields with the annual modulation filtered out is shown as a thin pink line. The monthly smoothed international sunspot number (R_{INT}; gray line) spans the range 0 to 160 from bottom to top of the figure. The "surge" in 1991–1992 is indicated by a dotted circle. A similar, but smaller surge is associated with the strong solar activity in late 2003.

the solar disk. The spatial resolution of the MWO data is much higher (20″ or better). To compare the MWO data with WSO we average corresponding high-resolution MWO observations into the WSO polemost aperture areas. The comparison serves as a check on the WSO data. The WSO data (http://quake.stanford.edu/~wso/Polar.ascii) are 30-day averages of the magnetic field measured in the polemost aperture calculated every 10 days. MWO data (kindly supplied by John Boyden) were averaged (weighted with limb-darkening) from binned coarse magnetograms using all bins within the area matching the WSO apertures, again averaged over 30 days and calculated every 10 days. The MWO instrument was upgraded in 1982, and a new operating procedure, aperture size, and data reduction program were put in place on 3 December 1985. Regression analysis comparing MWO with WSO yields a factor of 1.092 to convert MWO values to the WSO "standard" before 1985.92. For MWO data since then, the conversion factor was found to be 0.778. The factors are different mainly due to different aperture sizes. The binning also has the effect of making the annual modulation somewhat smaller for the MWO data. No attempt has been made to correct for magnetograph saturation [*Ulrich et al.*, 2002; *Svalgaard et al.*, 1978], the effect of which is to reduce the flux by a factor of about 2.

[6] During the course of a year, the solar rotation axis tips away (N pole ~ March 7) and towards (N pole ~ September 9) the observer by 7.25 degrees. Due to a combination of a strong concentration of the flux very near the pole and projection effects stemming from the line-of-sight field measurements, the observed polar fields vary by a factor of up to two through the year [*Svalgaard et al.*, 1978; *Babcock and Babcock*, 1955] during most of the solar cycle. The onset of this variation is the important new ingredient in determining the phase within the cycle at which to compare the polar field strength with the subsequent cycle amplitude.

[7] The polar field reversal is caused by unipolar magnetic flux from lower latitudes moving to the poles, canceling out opposite polarity flux already there, and eventually establishing new polar fields of reversed polarity [*Harvey*, 1996]. Because of the large aperture of the WSO instrument, the net flux over the aperture will be observed to be zero (the "apparent" reversal) about a year and a half before the last of the old flux has disappeared as opposite polarity flux moving up from lower latitudes begins to fill the equatorward portions of the aperture. The new flux is still not at the highest latitudes where projection effects are the strongest. The result is that the yearly modulation of the polar fields is very weak or absent for about three years following the (apparent) polar field reversal. Only after a significant amount of new flux has reached the near pole regions does the yearly modulation become visible again. This characteristic behavior is clearly seen in Figure 1. The four panels show the observed polar fields for each decade since 1970 (the start of each decade coinciding with apparent polar field reversals). Also marked are periods where the magnetic zero-levels were not well determined and noise levels were higher - at MWO (light blue at bottom of panel) before the instrument upgrade in 1982 and at WSO (light pink) during the interval November 2000 to July 2002. The difference between the amplitudes of the yearly modulation observed at MWO and at WSO is due to the difference in aperture sizes. At times, exceptional solar activity supplies extra (but shorter lived) magnetic flux "surges" to the polar caps, e.g., during 1991–1992 in the North. These events (both instrumental and solar) distract but little from the regular changes repeated through the four "polar-field cycles" shown (from reversal to reversal).

3. Results and Discussion

[8] Based on the four cycles observed so far we find that the polar fields and the yearly modulation become strong and well established about three years before sunspot minimum (for comparison, the sunspot numbers are also plotted in Figure 1). At this point the poloidal field is probably already feeding the solar dynamo and the first sunspots of the new cycle would be expected to appear at high latitudes about a year ahead of the statistical sunspot minimum [*Harvey*, 1996]. Other high-latitude solar phenomena belonging to the new cycle (ephemeral active regions, the coronal green-line emission and the torsional oscillation signal) are observed at this time as well [*Wilson*

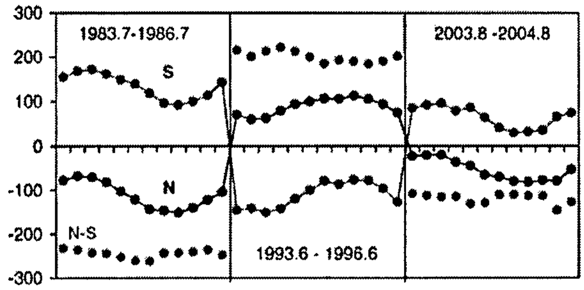

Figure 2. Average variation through the year of the polar fields (North - blue dots, South - red dots) measured at WSO for the three years before the minima in 1986.7 (left panel) and 1996.6 (middle panel) as well as data (right panel) for the past 12 months (i.e., the *first* only of the three years before the expected minimum in 2006.8). Also shown (green dots) are the differences between the North and the South polar fields.

et al., 1988]. The new activity starts the erosion of the polar fields, the net result being that the polar fields are strongest during an interval for about three years before sunspot minimum at the time when the yearly modulation becomes strong as well. We take the average field value over this interval to be the precursor indicator of the new cycle. *Bounar et al.* [1997] identified a similar optimum precursor interval (the last 30% of a cycle) in a study based on proxy (geomagnetic) data.

[9] Figure 2 shows the average variation through the year of the polar fields measured at WSO for the three years before the minima in 1986.7 and 1996.6 as well as data for the past 12 months (i.e., the first of the three years before the expected minimum in 2006.8). Also shown are the difference between the North and the South polar fields. We can compute average values of this difference (a measure of the strength of the Sun's axial magnetic dipole moment, DM) for each of the three epochs and compare them with Rmax for the following cycle (cycle 24 excepted, of course). The results are shown in Table 1. Assuming that Rmax = 0 when DM = 0, we fit a straight line through the origin to the two data points for cycle 22 and cycle 23: Rmax = 0.6286 DM (in μTesla) and compute Rmax from this regression line for cycles 22, 23 and 24. The absolute differences between the predicted and observed values are taken to be a measure of how well the procedure works (the only real measure as far as we are concerned). These differences are also shown in Table 1. Assuming that the average difference (3.6%) is representative, we assume that it can be used as a basis for estimating the uncertainty of the predicted value of cycle 24: $Rmax_{24} = 75.0 \pm 2.8$. Since the predictor for cycle 24 is based on only one year's worth of data rather than three, we conservatively (and admittedly, arbitrarily) increase the uncertainty to 8 yielding as our result: $Rmax_{24} = 75 \pm 8$. This would make cycle 24 potentially the smallest sunspot cycle since cycle 14 ($Rmax_{14} = 64$ in 1906). Monitoring the polar fields in the next few years might allow a refinement of the estimate of Rmax. An important advantage of the polar field precursor method is the significant lead-time of the prediction (about seven years ahead of the maximum) and its potential for continual (real-time) update as the cycle gets underway.

Table 1. Magnitude of the Sun's Dipole Moment (DM) Expressed as the Average Unsigned Difference Between the Two Polar Fields for the Three Epochs Shown in Figure 2: 1983.7–1986.7, 1993.6–1996.6, and 2003.8–2004.8 Compared to the Observed and Predicted (=0.6286 DM) Yearly Smoothed Rmax for the Following Cycles

Cycle	Dipole Moment μTesla ABS(North - South)	Observed Rmax	Predicted Rmax	Prediction Error
22	245.1 ± 2.7	158.5	154.1	2.9%
23	200.8 ± 3.6	120.8	126.2	4.3%
24	119.3 ± 3.2	?	**75.0**	3.6% (Assumed)

[10] Several other recent predictions [*Schatten*, 2003; *Schatten and Tobiska*, 2003; *Badalyan et al.*, 2001; *Duhau*, 2003; *Wang et al.*, 2002], but not all [*Tsirulnik et al.*, 1997; *Hathaway and Wilson*, 2004], also seem to indicate lower solar activity for the coming cycle(s). Such low cycles will be important for calibration of various empirical relationships between solar and interplanetary conditions and terrestrial phenomena, many of those derived during intervals of rather high solar activity [*Lockwood et al.*, 1999; *Svalgaard et al.*, 2003]. Average space weather might be "milder" with decreased solar activity, but the extreme events that dominate technological effects are not expected to disappear. In fact, they may become more common. Two of the eight strongest storms in the last ~150 years occurred during solar cycle 14 (Rmax = 64) [*Cliver and Svalgaard*, 2004], while three of the five largest 30 MeV solar energetic proton events since 1859 [*McCracken et al.*, 2001] occurred during cycle 13 (Rmax = 88).

[11] Figure 3 shows the time variation of the solar magnetic axial dipole moment expressed as the difference between the polar fields in the North and in the South [N-S]. Also plotted is the reverse difference between S and N [S-N]. The trend of decreasing dipole moment is particularly clear in Figure 3. The pattern shows two almost equal sized cycles (21 and 22) followed by a significantly smaller cycle (23), following by yet a smaller cycle (24).

[12] *Dikpati et al.* [2004] suggest that the magnetic "memory" of the solar cycle is 17–21 years and that therefore the polar fields at the end of cycle *n* might have a strong correlation with the subsurface toroidal fields of cycle *n*+2. This suggestion clearly has predictive power,

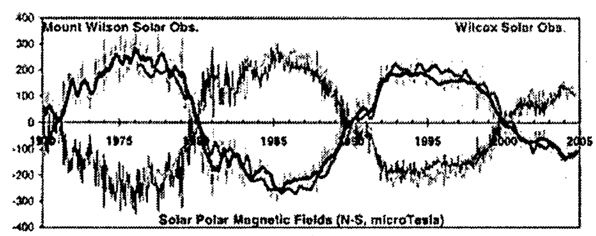

Figure 3. Time variation of the solar magnetic axial dipole moment (expressed as the difference between the polar fields in the North and in the South [N-S]). Also plotted is the difference between S and N [S-N]. MWO data is shown with bluish colors. WSO data is shown with reddish colors. Heavy lines show 12-month running mean values of the N-S difference.

but, to date, no specific prediction based on the model of Dikpati et al. has been issued. Our Figure 3 does not show support for an n, $n+2$ relation. The coming cycle 24 has the potential to become a test of their model.

[13] The solar polar fields are important in supplying most of the heliospheric magnetic flux during solar minimum conditions. With weaker polar fields, the interplanetary magnetic fields that the Ulysses space probe will measure during its next polar passes in 2007–2008 are therefore expected to be significantly lower than during the 1994–1995 polar passes.

[14] **Acknowledgment.** We acknowledge the use of magnetic data from the Wilcox Solar Observatory, from Mount Wilson Observatory, and of sunspot data from SIDC, RWC Belgium, World Data Center for the Sunspot Index, Royal Observatory of Belgium (years 1890–2004).

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